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SHORTER COMMUNICATION

ON THE CHARACTERISTICS OF HEAT AND MASS TRANSFER FROM A ROTATING DISK WITH SINK FLOW

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NOMENCLATURE

(I) In an open environment

$$\overline{Nu}_\infty, \overline{Sh}_\infty, = f\left(Re_r, Re_s, Gr, Pr \text{ or } Sc, \frac{r_0 - r'_s}{r_0}\right)$$

where:

$\overline{Nu}_\infty, = \dfrac{\bar{\alpha}(r_0 - r'_s)}{\lambda}$: average Nusselt number;

$\bar{\alpha}, = \dfrac{0.86VI - q_r - q_s - Q_s\gamma_a C_{pa}(t_0 - t_i)}{A_0(t_{sm} - t_\infty)}$:
average heat-transfer coefficient;

$\overline{Sh}_\infty, = \dfrac{\overline{kc}(r_0 - r'_s)}{D_v}$: average Sherwood number;

$\overline{kc}, = \dfrac{\bar{m}R_v T_{sm}}{A_0 P_{vs}}$:
average mass-transfer coefficient;

$Re_r, = \dfrac{V_u \cdot r_0}{v} = \dfrac{\omega r_0^2}{v}$;
rotational Reynolds number;

$Re_s, = \dfrac{V_i \cdot ds}{v}$: sink flow Reynolds number;

$V_i, = \dfrac{Q_s}{\pi d_s^2/4}$; velocity of sink flow;

$Gr, = \dfrac{g \cdot \beta \cdot \Delta T(d_0 - d'_s)^3}{v^2}$:
average Grashof number;

$Pr, = \dfrac{v}{a}$: Prandtl number;

$Sc, = \dfrac{v}{D_r}$: Schmidt number;

$\dfrac{r_0 - r'_s}{r_0}$, reference length ratio of heating surface to that of a rotating disk;

Q_s, the rate of sink flow;

q_r, heat loss by thermal radiation;

q_s, heat loss by convection from side surfaces of saucer;

γ_a, specific weight of fluid;

C_{pa}, specific heat of fluid at constant pressure;

D_v, diffusion coefficient of naphthalene into air.

(II) In semi-closed space with a stationary disk

$\overline{Nu}_c, \overline{Sh}_c, = F(Re_r, Re_s, Gr, Pr \text{ or } Sc, Ta, Re_c, d_1/d_0, c/d_0)$
where:

$Ta, = \dfrac{\omega c^2}{v}$: Taylor number;

$Re_c, = \dfrac{V_i c}{v}$: clearance Reynolds number;

d_1/d_0, diameter ratio of stationary to rotating disk;

c/d_0, clearance ratio of spacing to diameter of a rotating disk.

INTRODUCTION

THE SOLUTION of the so-called injection or suction problem for an effective control of boundary layer and details of functions of the heat-transfer characteristics in industry were brought to light recently [1, 2]. In general this problem could be resumed to come under injection or suction from the whole surface of solid body for effective applications. Applications of injection or suction problem to heat transfer characteristics from a rotating disk [3–5] have also been reported over the past decade. Moreover, heat-transfer analysis for semi-closed rotating disk with source flow has been found to be available to cool [6–8] high speed memory disks of electronic computers or impellers of cryogenic pumps. There are many fundamental differences in hydrodynamical characteristics of boundary layer and those of heat transfer between additional flow from the whole surface and that from a slit or hole [9].

The authors experimentally examined effects of sink flow suctioned into a 6 mm pipe located at the center of a disk on the convective heat- and mass-transfer characteristics from a rotating disk (I) in open air and (II) in semi-closed space with a confronting stationary disk. Accordingly, the formation of boundary layer on a rotating disk in this experiment basically differs from that analysed by Sparrow and Gregg [3] for a rotating disk with injection or suction from the whole surface. With both cases connected, they cannot be expressed in a series of equations which are characterized by area ratio of sink flow port to the surface of a rotating disk, $(d_s/d_0)^2$.

EXPERIMENTAL APPARATUS

Figure 1 shows a schematic view of the experimental apparatus. A circular pipe ⑤ of 6 mm in inner diameter and $d'_s = 2r'_s$ of 8, 10, 12 and 16 mm in outer diameters and with
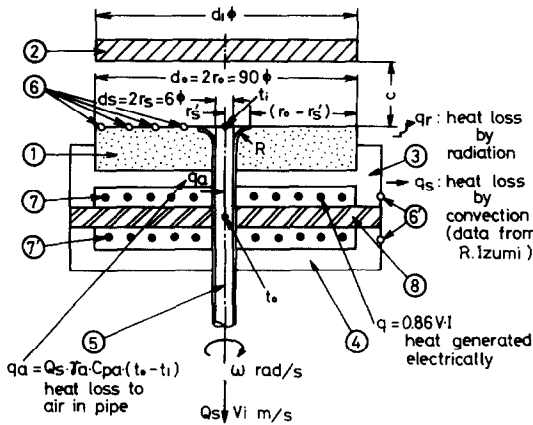
FIG. 1. A schematic view of experimental apparatus: (1) is a rotating disk of naphthalene: (2) is a stationary disk of polycarbonate; and (3) is a saucer of brass, which contains naphthalene layer and an electric heater.

its center on an axis of disk rotation, is provided for air flow suctioned by a rotary diffuser through a surge tank and a flowmeter. The rate of suctioned air Q_s is 0, 0.1, 0.2, 0.3, 0.4 and $0.5\,\mathrm{m}^3$(N.T.P.)/h and disk revolution speed n is 0, 100, 200, 300, 400 and 600 rev/min. A confronting stationary disk (polycarbonate plate) is placed coaxial and parallel to the rotating disk; its diameters d_1 are 20, 40, 60, 90 and 180 mm, and the spacing between the stationary and rotating disks is arranged in 1, 2, 3, 5, 7, 10, 20, 30, 50 and 90 mm. Each quantity is put in order of the moduli mentioned above as a result of dimensional analysis.

EXPERIMENTAL RESULTS AND CONSIDERATIONS

I. *Heat and mass transfer from a rotating disk in open air*

Figure 2 indicates the effect of sink flow on the average Sherwood numbers $\overline{Sh}_r$ changing from $\overline{Sh}_0$ at $Q_s = 0$. The average Sherwood numbers $\overline{Sh}_0$ for each rotation speed at $Q_s = 0$ obtained in this experiment are defined as $\overline{Sh}_0 = kc(r_0 - r_s')/D_r$ with a reference length deduced by considering that the concentration boundary layer develops from $r = r_s'$. The Sherwood numbers $\overline{Sh}_0$ are here arranged to correspond to their rotational Reynolds numbers $Re_r = (V_0 \cdot r_0)/v$.

$$\overline{Sh}_0 = 0.955 Re_r^{0.45} \qquad (1)$$

where the authors define the rotational Reynolds number applying the concept that the concentration boundary layer develops by centrifugal force due to the acceleration of V_0^2/r_0 at $r = r_0$. $\overline{Sh}_r$, as shown in this figure, gradually increase and have almost the same rate of increment for each rotation. Supposing the extremity of each $\overline{Sh}_r$ in Fig. 2, the authors can obtain $\overline{Sh}_r/\overline{Sh}_0 = 1.0$ at the point of $Re_s = 0$ and set the experimental equation as follows:

$$\overline{Sh}_r = 0.955 Re_r^{0.45} + 0.252 Re_s^{0.65} / Re_r^{0.20} \qquad (2)$$

where the first right hand term in the above equation indicates equation (1) and the second term represents the effect of sink flow by which it increases the local mass-transfer coefficients kc near the suction orifice. Besides equation (2), from these experimental data the other approximate expression is induced as,

$$\overline{Sh}_r = 1.215 Re_r^{0.35} Re_s^{0.10}. \qquad (3)$$

The effect of sink flow in the above equation coincides quantitatively with that of the result by Kapinos [8], who obtained an effect of injected flow from a confronting corotating disk as an accelerative flow into the spacing between two disks in his experimental equation of $\overline{Nu} \sim Q_s^{0.10}$. Both heat and mass transfers are observed here and are arranged by Colburn's J-factors in maximum deviation of 7%. The similarity between them is proved.

II. *Heat and mass transfer from a rotating disk in semi-closed space with a confronting stationary disk*

Figure 3 shows the important factor $Re_s/Ta = V_i/\omega c$ in abscissa governing the state of flow in the spacing between two disks.

This factor means that the inertia force by suction and the Coriolis force by rotation govern the flows in the spacing.

All rates of mass transfer are not governed only by the rate or velocity of sink flow; they vary by the combination of suction flow and the radial swirl in the spacing whose vectors differ. This variation, as shown in Fig. 3, does not change in a monotonous feature. An experimental equation can be described as follows, taking advantage of the fact that the experimental data vary in algebraical summary of the following form: $y = (1 + e^x - x e^{-x}) \cdot y_0$, not always in physical aspect.

$$\frac{\overline{Sh}_c}{\overline{Sh}_r} = \left[1 + 1.089 \exp\left\{ 1.675\left(\ln\frac{V_i}{\omega c} - 6.213 \right) \right\} \right.$$
$$\left. - 0.623\left(\ln\frac{V_i}{\omega c} - 2.65 \right) \exp\left\{ -\left(0.623 \ln\frac{V_i}{\omega c} - 1.65 \right)^2 \right\} \right] \qquad (4)$$
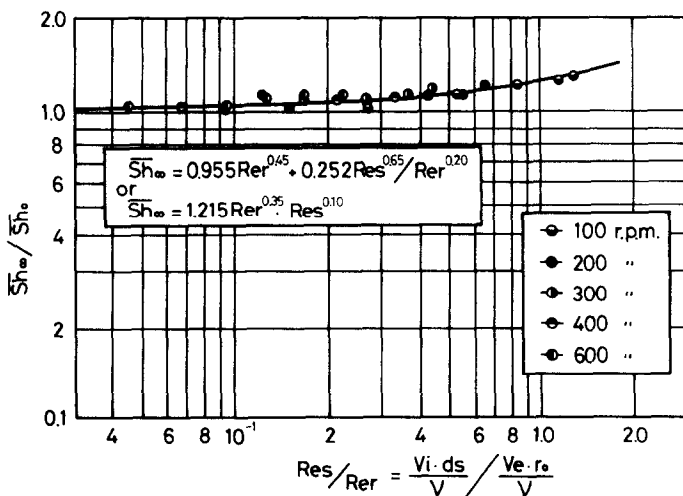

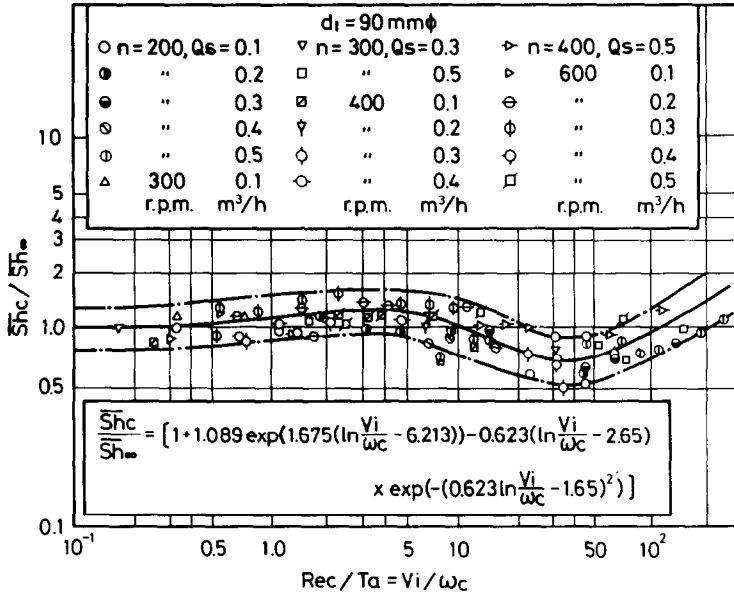FIG. 2. The experimental equations for the effect of sink flow.

FIG. 3. An experimental equation for mass transfers from a shrouded rotating disk under an effect of sink flow.

The mass transfer depends on the modulus of Re_c/Ta which represents the relationship between the rotational flow and suction flow in the spacing.

$$V_i/\omega_c \lesssim 10, \quad \overline{Sh}_c/\overline{Sh}_\infty > 1.0.$$

The effect of suction flow to increase mass transfer is slight, because it is the same as in the case of experiment (1).

$$10 < V_i/\omega_c < 50, \quad \overline{Sh}_c/\overline{Sh}_\infty < 1.0.$$

In particular, the smaller the clearance c is, the larger the skin frictions on both surfaces of the stationary and rotating disks become. Namely, stagnation of naphthalene vapor appears.

$$50 \ll V_i/\omega_c, \quad \overline{Sh}_c/\overline{Sh}_\infty > 1.0.$$

The spacing between two disks is occupied by the strong suction flow accompanying many vortexes which generated at the peripheral edges of the disks and enhancing mass transfer.

Since the velocity of suction flow is measured in the pipe of suction, the actual suction flow in the spacing is weak and has little effect of $\overline{Sh}_c$. In order that the suction flow makes $\overline{Sh}_c$ increase markedly, the velocity of sink flow must be 100 times the product of ω and c. $\overline{Sh}_c$ would be more or less than $\overline{Sh}_\infty$. Therefore, some practical applications are possible, if a right value of V_i/ω_c is selected, such as to increase or decrease cooling effects.

CONCLUSIONS

The characteristics of heat and mass transfer were obtained on a rotating disk with sink flow suctioned into an orifice of $d_s = 6$ mm in diameter at the center of the rotating disk, with and without a stationary disk. This theme is said to be available for the cooling method to rotating bodies proposed by Kreith or Kapinos. The following conclusions were obtained.

(1) The present flow pattern above the rotating disk in open air basically differs from the one caused by the homogeneous suction, because effects of suction flow in this case upon the boundary layer extend not in a large scale but in a limited range. Therefore, the characteristics of heat and mass transfer are also different and can be expressed as follows:

$$\overline{Sh}_\infty = 0.955 Re_r^{0.45} + 0.252 Re_s^{0.65}/Re_r^{0.20}$$

or

$$\overline{Sh}_\infty = 1.215 Re_r^{0.35} Re_s^{0.10}.$$

(2) Such uniform increase of $\overline{Sh}_\infty$ is attributed to the flow induced by suction rather than the flow above a rotating disk due to the rotational flow field and it makes kc increase near the suction orifice. The larger the Q_s, the larger the $\overline{Sh}_\infty$.

(3) The similarity between heat and mass transfer is proved by the identical variation in behavior of the two which is brought about by means of Colburn's J-factors of

$$J_H = Nu_\infty/Re_r \cdot Pr^{1/3} \text{ and } J_M = \overline{Sh}_\infty/Re_r \cdot Sc^{1/3}.$$

(4) The authors observe in regard to the characteristics of heat and mass transfer from a rotating disk with a stationary disk that $\overline{Sh}_c \lessgtr \overline{Sh}_\infty$ is dependent on the values of Re_s/Re_r or $Re_c/Ta = V_i/\omega_c$ expressing the state of the flow with rotation and suction. And this can be used in many ways as to increase or decrease the cooling effect.

(5) In the region of $Re_c/Ta > 50$ the suction flow gains ascendancy and it occupies the spacing as forced flow. Then it makes the mass-transfer increase evenly and intensifies cooling effects on the rotating disk.

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